

Photon-induced Background for Dilepton Searches and Measurements in pp Collisions at 13 TeV

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Abstract

The production of high invariant mass opposite sign lepton pairs in proton-proton collisions at the LHC is dominated by the Drell-Yan process. In addition to this photon or Z exchange mediated mechanism, gamma-gamma collisions, where photons radiated by the incoming protons collide, can produce lepton pairs. This is an important additional source of background for high mass resonant (like Z') or non-resonant (like contact interactions) searches. In this paper detailed calculations of the Drell-Yan and photon-induced cross sections in the typical acceptance of a multi-purpose LHC detector at center of mass energy 13 TeV are presented. The hint for a diphoton excess at a mass around 750 GeV, reported by the ATLAS and CMS experiments from the analysis of the 2015 data at 13 TeV, raises the possibility that such an excess could be produced through gamma-gamma collisions. A good theoretical understanding and measurements in the dilepton channels at these energies can help to elucidate this production hypothesis.

1 Introduction

The Standard Model (SM) of particle physics has been tested extensively at collider energies. Searches for new physics phenomena in dilepton (electron or muon) final states provide clean signatures. The CMS and ATLAS collaborations at the LHC have searched for resonant or non-resonant effects beyond the SM, see e.g [1, 2, 3, 4].

The backgrounds at high invariant masses are dominated by the Drell-Yan (DY) process of opposite sign lepton pair production, mediated through photon or Z exchange from the initial partons in the incoming protons. An alternative route to produce lepton pairs is in gamma-gamma collisions, where photons radiated by the incoming protons collide. To calculate this process, usually labeled photon-induced (PI) background in various searches, we need parton density functions (PDF) of the protons including the photon component. A similar process, two-photon collisions, where the photons originate from electrons and positrons, has been studied extensively e.g. at LEP2 [5].

The hint for a diphoton excess [6, 7] at a mass around 750 GeV, reported by the ATLAS and CMS collaborations from the analysis of the 2015 data at 13 TeV, has sparked a flurry of phenomenological activity. One hypothesis is that a spin 0 scalar is produced through gamma-gamma collisions [8]. Clearly a good theoretical understanding and measurements at these energies can help to elucidate this hypothesis.

2 The Photon PDF

Quantum Electrodynamics (QED) introduces corrections to the parton evolution. As a result, we have to include photon parton distributions $\gamma(x, Q^2)$ for the proton and the neutron, and part of the proton (neutron) momentum is carried by the photons. The PDF depends on the parton momentum fraction - Bjorken x , and the momentum transfer Q^2 .

In [9] a global analysis of deep inelastic and hard scattering data was performed and the photon PDF was extracted. It is available from the LHAPDF library [10, 11, 12] as MRST2004qed. This PDF set uses a model for the starting distribution at momentum transfer $Q_0^2 = 1 \text{ GeV}^2$. For the photon radiation cutoff there are two options:

1. Cutoff at the current quark masses of 6 (10) MeV for up (down) quarks. We will label this PDF as Mem0 (corresponding to member 0 in the LHAPDF library).
2. Cutoff at the constituent quark masses of 300 MeV for up and down quarks. We will label this PDF as Mem1 (corresponding to member 1 in the LHAPDF library). This choice reduces the momentum carried by the photon, as higher masses produce less radiation.

The authors of [9] argue that, photon radiation being a perturbative QED effect, current quark masses are more appropriate; correspondingly this option is the default member 0. They support this argument with an analysis of the then available ZEUS collaboration data [13] for the reaction:

$$ep \rightarrow e\gamma X \quad (1)$$

measured in a narrow range around $x_\gamma \sim 0.005$. This is the most direct measurement of the photon PDF, as the photon contribution is at the leading perturbative order.

In [14] a different starting photon parametrization and a combined quantum chromodynamics QCD and QED evolution is used. In addition, data on Drell-Yan, W and Z production from the LHC is used to constrain the photon PDF. The LHC data places relatively weak constraints, resulting in large PDF uncertainties. We will use NNPDF23qed, as provided by LHAPDF.

In [15] a generalization of the MRST approach is applied to derive CT14QED sets. The initial photon distribution is defined by the initial photon momentum fraction p_0^γ at scale $Q_0 = 1.295 \text{ GeV}$. Newer ZEUS data on deep inelastic scattering with isolated photons [16] is used to constrain the photon PDF. The authors find

$$p_0^\gamma \leq 0.14\% \quad (2)$$

at 90% confidence level (CL). They conclude that the Mem0 option of MRST2004qed, using current quark masses, is ruled out by the data, and recommend using initial p_0^γ values between 0 and 0.14%. The constituent quark masses option of MRST2004qed is allowed, as well as the initial NNPDF parametrization at low Q^2 . At high Q^2 the CT14QED sets are compatible with MRST2004qed (Mem1), while the NNPDF23qed set shows sizeable deviations both at low and high x values. The implications of this for LHC predictions will be analyzed in detail in the next section.

In Drell-Yan, W and Z production at the LHC the photon contribution is suppressed by a factor $O(\alpha/\alpha_s)$ compared to the canonical quark-antiquark contribution, thus providing relatively weak constraints on the photon PDF, especially where high precision data is scarce, e.g. at high masses or high x values. The sensitivity can be improved in measurements where the photon contribution is enhanced by selecting exclusive dimuon pair production in elastic, single dissociative and double dissociative pp collisions [17, 18]. These CMS measurements are used in [19] to update the CT14QED analysis. The authors conclude that

$$p_0^\gamma \leq 0.09\% \text{ at } 68\% \text{ CL} \quad (3)$$

$$p_0^\gamma \leq 0.13\% \text{ at } 90\% \text{ CL} \quad (4)$$

consistent with the ZEUS data analysis. At 250 GeV a CT14QED PDF with momentum fraction 0.09% is compatible with MRST2004qed Mem1 and NNPDF23qed, while MRST Mem0 is higher. Above 1 TeV NNPDF23qed exceeds all other PDFs (even Mem0), while Mem1 is compatible with CT14QED throughout.

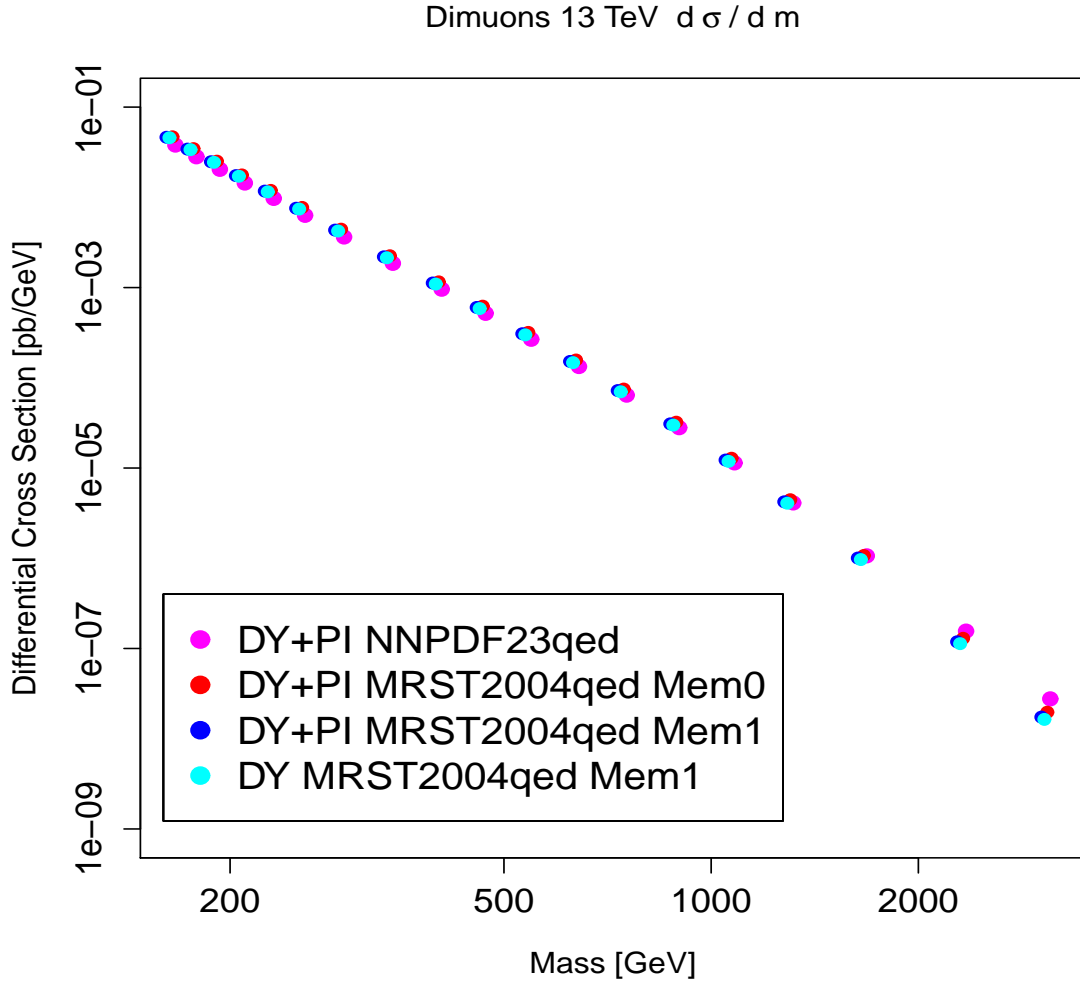


Figure 1: Differential cross sections for DY and PI at 13 TeV in the search acceptance.

3 Results

The calculations for the Drell-Yan process and the photon-induced background are performed with the program FEWZ [20]. The G_μ input scheme is used. The PDFs considered in this study are MRST2004qed and NNPDF23qed. Full electroweak corrections at next to leading order (NLO) are computed (the flag `EW control = 0` is used). QCD effects are computed at leading order (LO). When the PI background is included we label the results DY+PI. When only the DY process is included we label the results DY. Most of the presented plots show ratios of cross sections where some uncertainties cancel, and the influence of missing higher orders is reduced. Calculations for dimuons in the acceptance of a generic general purpose LHC experiment are presented: both outgoing leptons are required to have pseudorapidity $|\eta| < 2.4$. The results for dielectrons are very similar.

We distinguish two cases:

1. “Search” acceptance: relatively hard cuts suitable for high masses are used - cuts on the transverse momenta $p_T > 50$ GeV for both leptons are applied.
2. “DY” acceptance: relatively soft cuts suitable also for low masses are used - asymmetric cuts on the transverse momenta $p_T > 20$ (10) GeV for the harder (softer) lepton are applied. These cuts allow precision measurements both above and below the Z peak.

In Figure 1 the differential cross sections as function of mass are shown. The substantial differences at higher masses are visible even in this double logarithmic scale plot. As the validity range of MRST2004qed is limited by $Q_{Max} = 3162.28$ GeV, we show plots up to this value. This covers early searches but will not be sufficient with the accumulation of LHC luminosity at 13 TeV. It is possible to extrapolate to higher masses, or alternatively use the newest photon PDFs like CT14QED.

It is worth noting that the absolute values of the cross sections do not agree with the values presented in [14], see e.g. their Figure 23. It appears that the differential cross section there is not properly normalized, and it exhibits an unphysical “kink” around 1.2 TeV.

In Figure 2 the predictions for the cross section ratio (DY+PI)/DY for different photon PDFs are shown in the Search acceptance. The bottom plot shows the same ratios including the PDF uncertainty for NNPDF23qed. As can be seen, the latter predictions differ substantially from the MRST2004qed results, especially at masses above 1 TeV. Moreover, the PDF uncertainty exceeds the size of the PI effect, limiting the predictive power of this calculation. Clearly this is related to the lack of experimental data at high momentum transfers, the accumulation of much more data in Run 2 certainly will help.

The cross sections in the DY acceptance for the two members of MRST2004qed are compared in detail in Figure 3. The DY predictions are almost identical, as expected, while the (DY+PI) results differ substantially. As discussed in the previous section, the experimental data favor the Mem1 option, producing the smallest PI effects.

In Figure 4 the cross sections in the Search acceptance for the two members of MRST2004qed are compared in detail. Again the DY predictions are almost identical, as expected, while the (DY+PI) results differ substantially. As discussed in the previous section, the experimental data favor the Mem1 option, producing the smallest PI effects, important for resonant and especially for non-resonant searches in the TeV region.

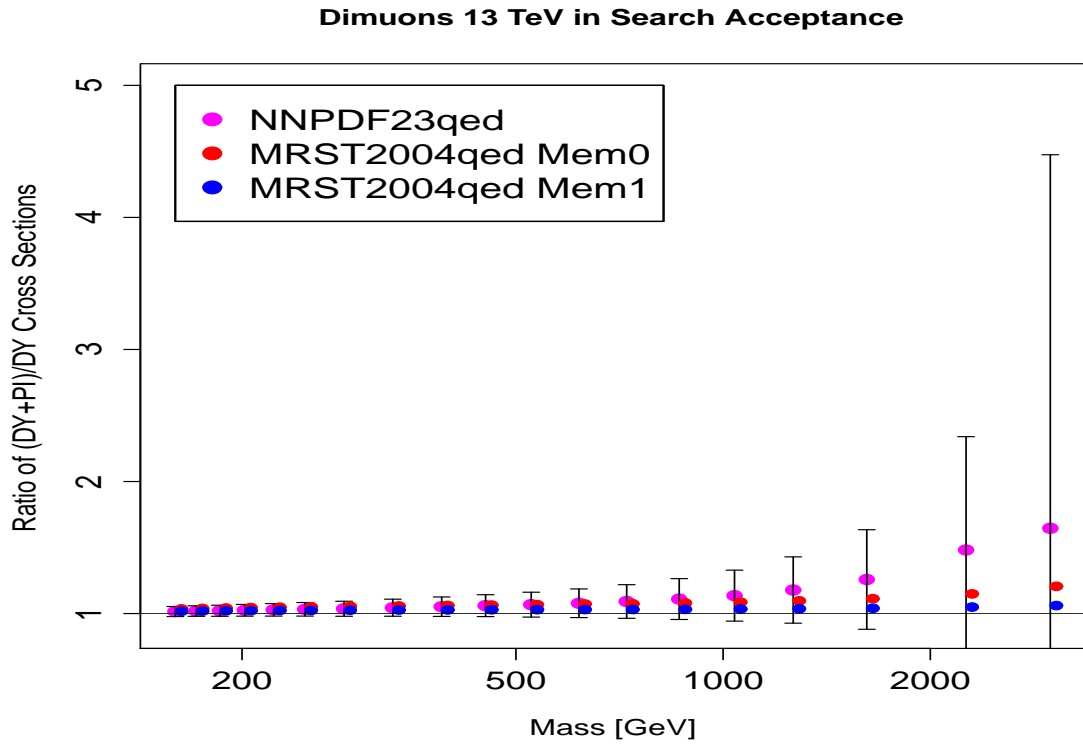
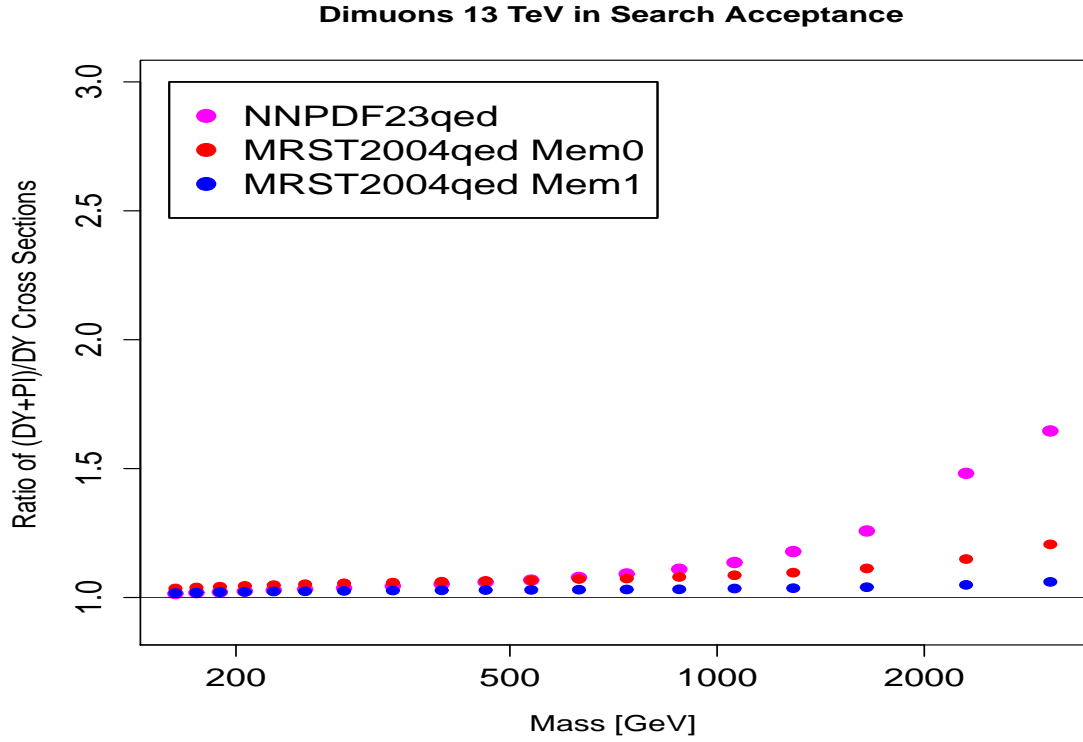


Figure 2: Top: ratios of cross sections (DY+PI)/DY for different PDFs in the Search acceptance. Bottom: same, but including the PDF uncertainties for NNPDF23qed.

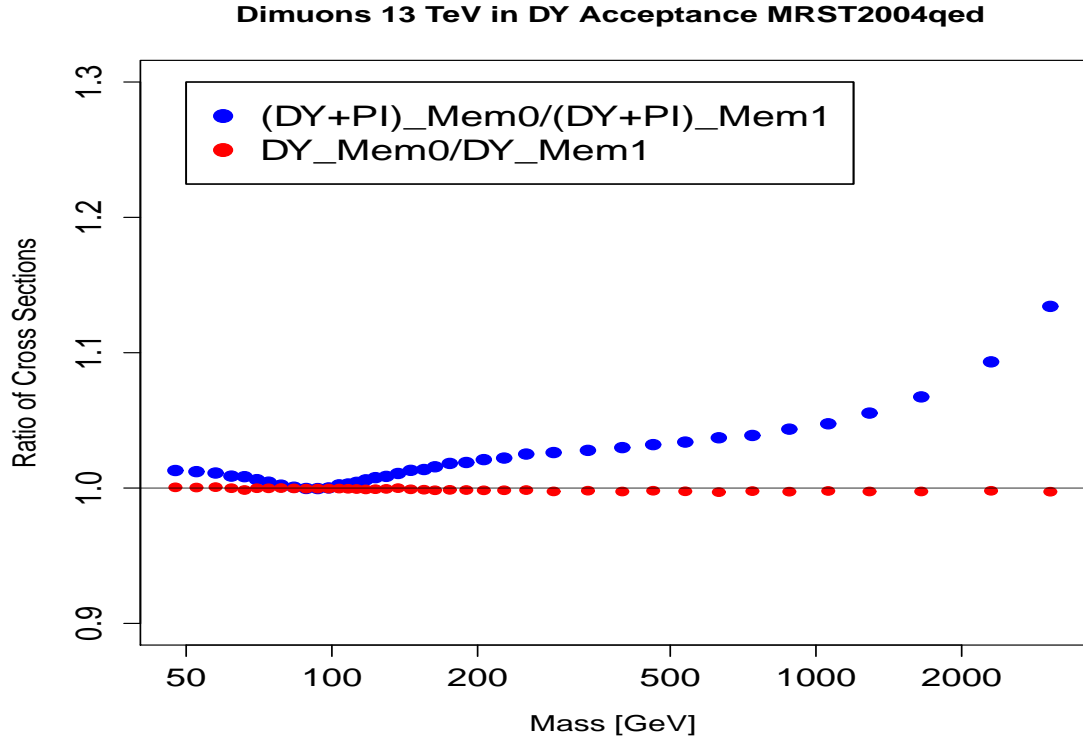
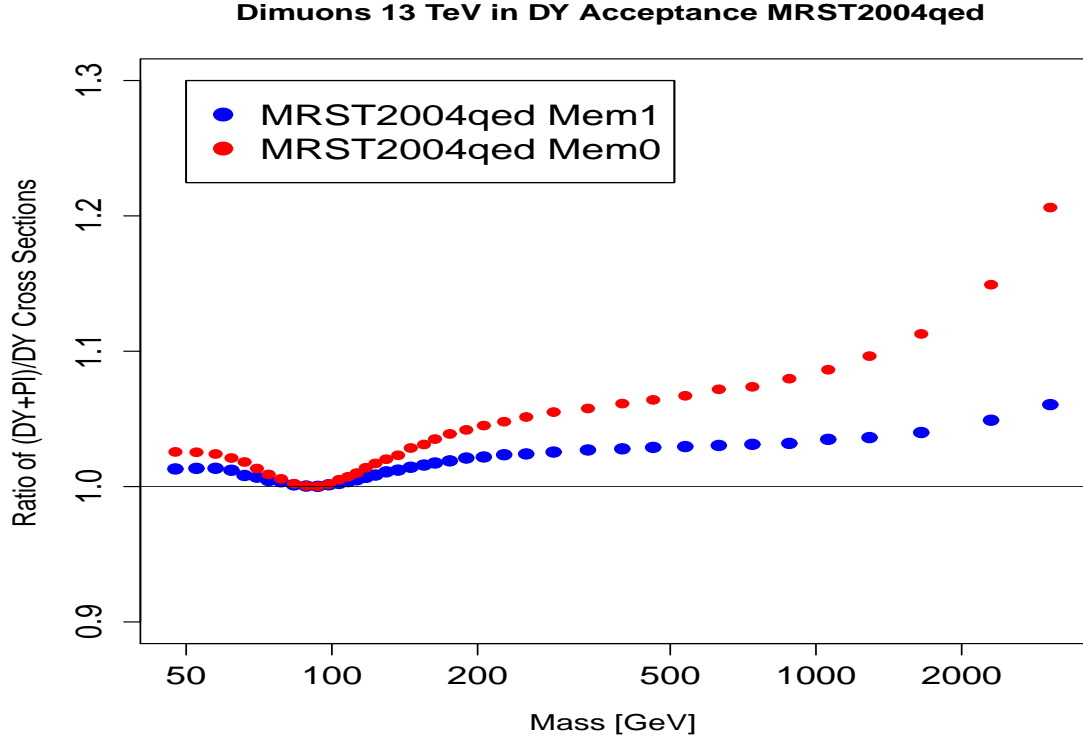


Figure 3: Top: ratios of cross sections $(DY+PI)/DY$ for the two members of MRST2004qed in the DY acceptance. Bottom: ratio of $(DY+PI)$ for the two members (blue), and ratio of the DY cross sections for the two members (red), showing that the DY predictions are almost identical while the $(DY+PI)$ predictions differ substantially.

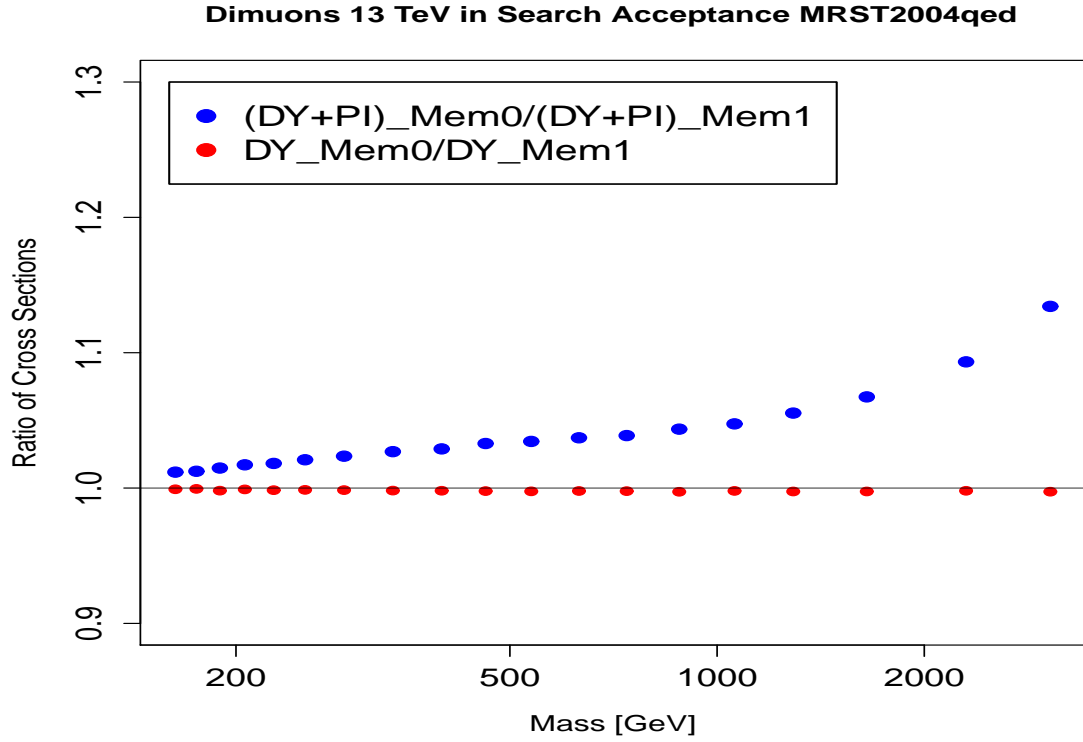
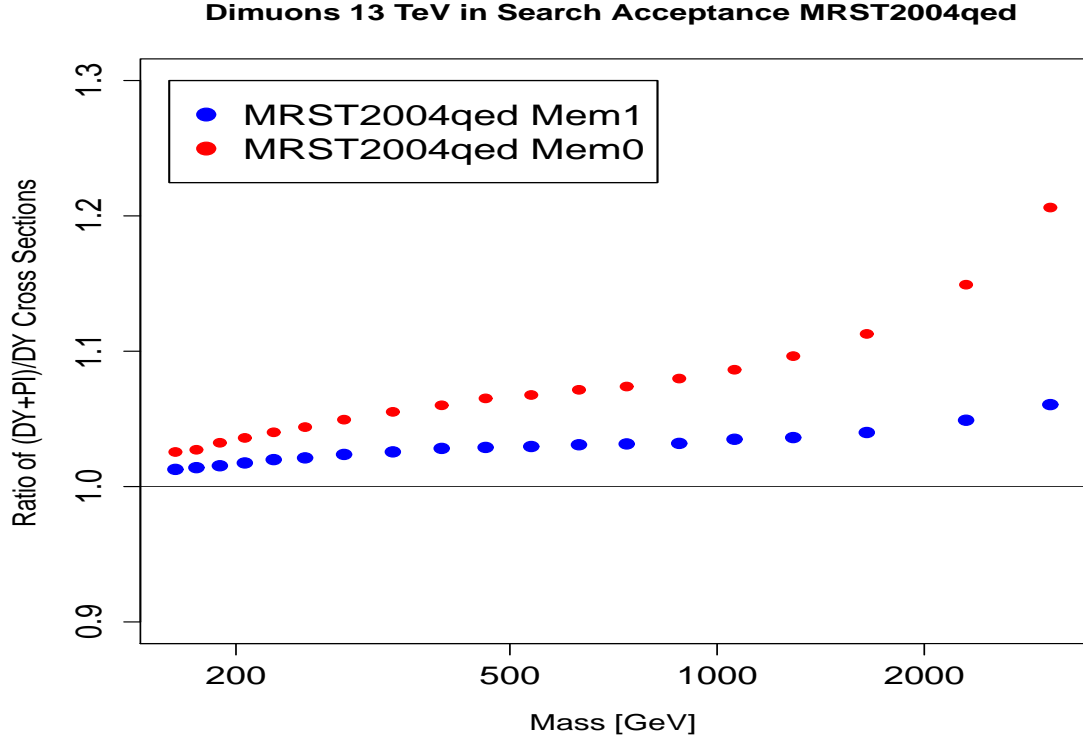


Figure 4: Top: ratios of cross sections $(DY+PI)/DY$ for the two members of MRST2004qed in the Search acceptance. Bottom: ratio of $(DY+PI)$ for the two members (blue), and ratio of the DY cross sections for the two members (red), showing that the DY predictions are almost identical while the $(DY+PI)$ predictions differ substantially.

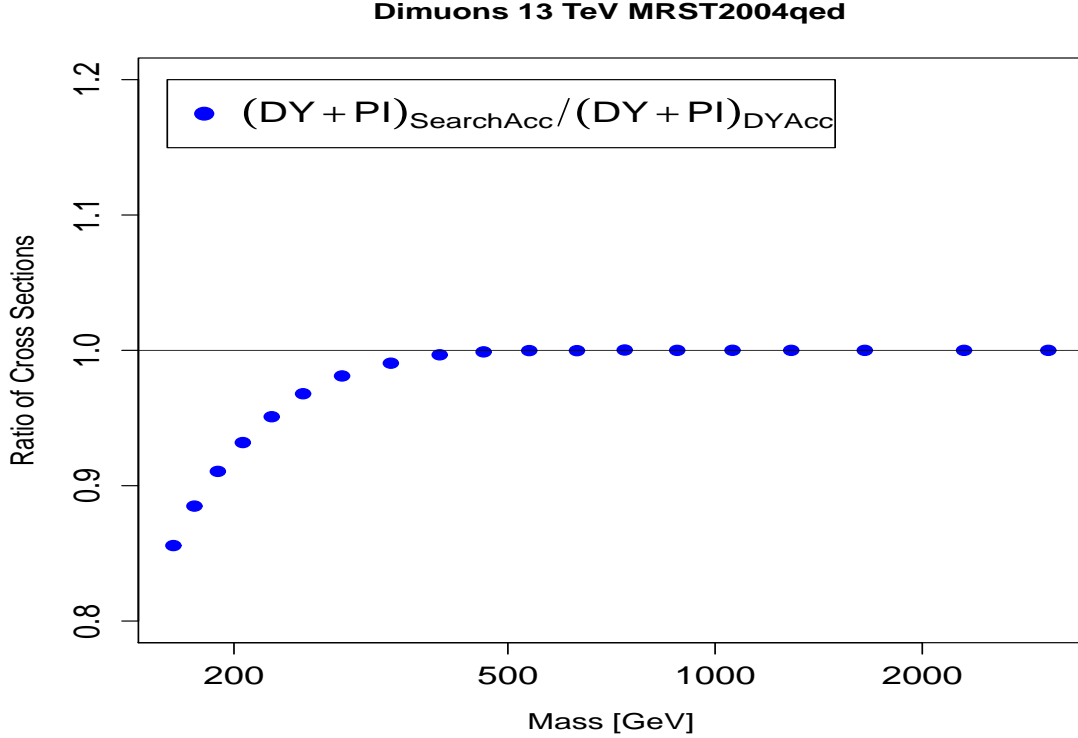


Figure 5: Ratios of cross sections (DY+PI) for MRST2004qed in the Search and DY acceptances. At high mass the ratio approaches unity.

An important question arises: can the PI background be suppressed by a set of cuts which does not reduce substantially the signal efficiency. As shown in Figure 5, the harder p_T cuts on the outgoing leptons do not reduce the (DY+PI) cross sections above ~ 400 GeV, so they have no impact on the interesting high mass region.

In Figure 6 the rapidity distribution of the ratio (DY+PI)/DY using MRST2004qed Mem1 for two invariant mass bins is shown. The first bin is chosen to include the region where the ATLAS and CMS collaborations have reported a hint for a diphoton excess in the first Run 2 data. The PI effects are small for this bin, peaking in the center of the detector, almost vanishing at rapidities $|y| \sim 2$, and rising again at the acceptance edges. The rapidity (y) distribution is symmetric around zero, as expected. This is a good technical check that the calculation has been performed to high enough precision, here to relative precision 0.1%. If the integration accuracy of the semi-analytic calculation is not high enough, fluctuations and asymmetries begin to appear. The second bin is a typical search bin from 2–3 TeV; here again the PI effects are strongest in the center and are diminishing at the acceptance edges. As the acceptance interval is shorter, the PI effects have no room to rise again. The fact that at high mass the PI effects are strongest in the center of the detector makes their suppression very difficult. In addition, as these effects are small, especially if MRST2004qed Mem1 is used, there appears to be no pressing need for additional cuts, which could reduce the signal efficiency.

In Figure 7 the rapidity distribution of the ratio (DY+PI)/DY using NNPDF23qed for the same two invariant mass bins is shown. This time the PI effects are substantially higher for the first bin, again peaking in the center of the detector, reduced at rapidities

$|y| \sim 2$, and rising again at the acceptance edges. For the second bin the picture changes both qualitatively and quantitatively. A dramatic rise at the acceptance edges is seen, the vertical scale for the ratio had to be increased from 1.2 to 10. The lack of experimental and theory constraints result in the NNPDF23qed becoming “unhinged” at high invariant masses. It is used in the diphoton analysis of [8]. As noted in [19], the use of MRST2004qed Mem1 appears to produce more realistic results.

The calculations of photon-induced effects in the dilepton channels lead to the same conclusion: MRST2004qed or newer well behaved photon PDFs are recommended for the exploration of the LHC search region at high mass. With the accumulation of LHC luminosity the PI effects around 750 GeV and higher can be measured in the dilepton channels, improving the knowledge of the photon PDF.

4 KISS

Before leaving this topic, it is tempting to compare the sophisticated calculations presented above to a simple estimate. Assuming that the cross section ratio PI/DY is proportional to the QED and QCD coupling strengths $\mathcal{O}(\alpha/\alpha_s)$, if only the photon exchange is considered for Drell-Yan, and taking the renormalization group running of the couplings to 2-loop into account, a rough estimate can be derived. In order to obtain the full ratio, the Z exchange and γZ interference terms are added. The results are compared to the FEWZ calculations with MRST2004qed in Figure 8. As is evident, good agreement with the MRST2004qed predictions is observed, with the KISS estimate well inside the band formed by the two PDF members.

5 Outlook

The production of high invariant mass opposite sign lepton pairs in proton-proton collisions at the LHC is an important search region for manifestations of new physics, and for tests of the Standard Model at highest momentum transfers. Gamma-gamma collisions, where photons radiated by the incoming protons collide, will produce additional lepton pairs - source of background for high mass resonant (like Z') or non-resonant (like contact interactions) searches. In this paper detailed calculations of the Drell-Yan and photon-induced cross sections in the typical acceptance of a multi-purpose LHC detector at center of mass energy 13 TeV are presented. The use of MRST2004qed in the constituent mass option or newer well behaved photon PDFs is recommended for the exploration of the LHC search region at high mass. In addition, a simple estimate of the PI effects is shown to work well from the Z peak to the high mass region.

The hint for a diphoton excess, reported by ATLAS and CMS at a mass around 750 GeV, makes good theoretical understanding and measurements in the dilepton channels at these energies very desirable in order to explore the hypothesis that such an excess could be produced through gamma-gamma collisions.

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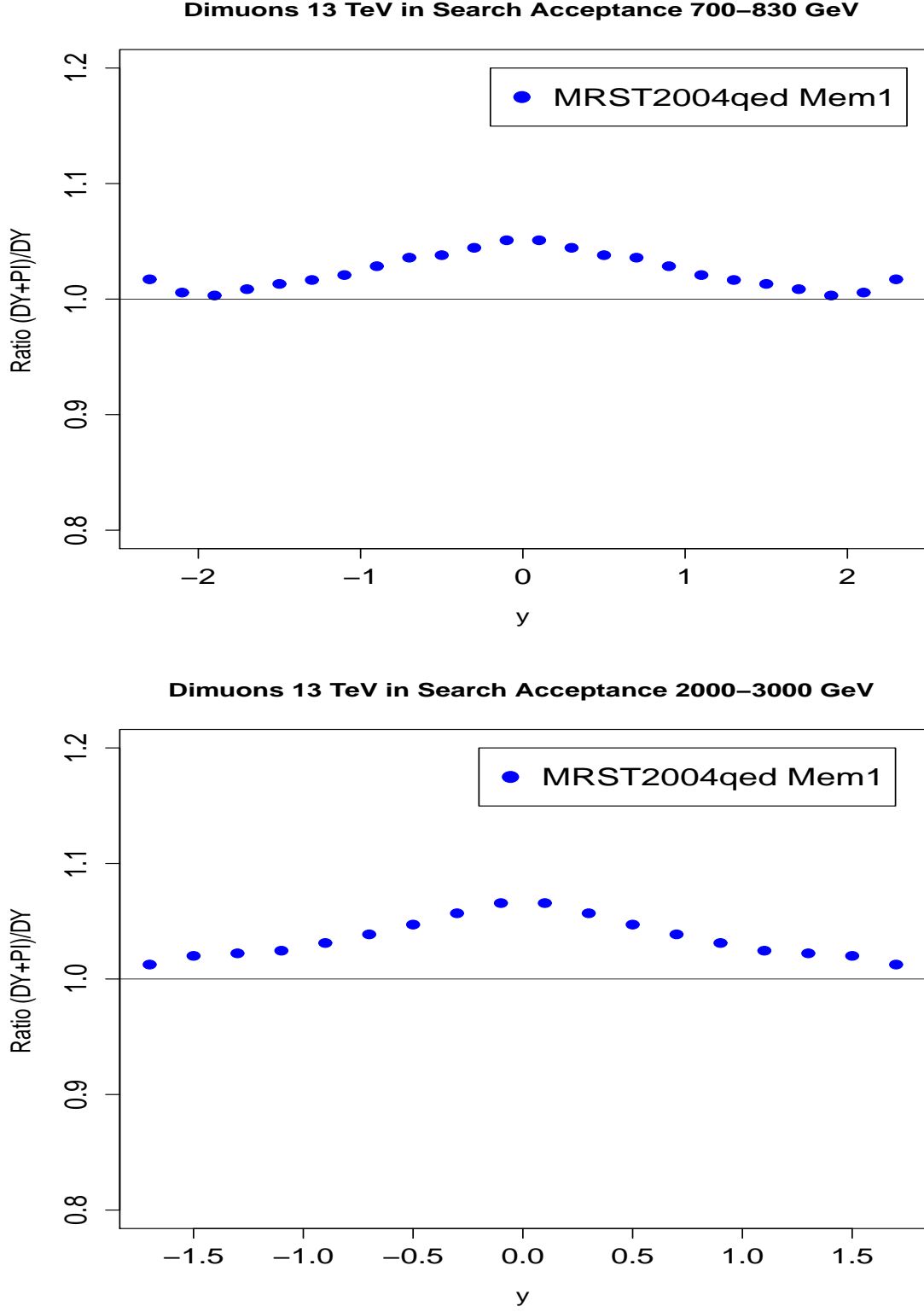


Figure 6: Top: rapidity distribution for $(DY+PI)/DY$ using MRST2004qed Mem1 for invariant masses 700–830 GeV. Bottom: rapidity distribution for the same ratio for invariant masses 2–3 TeV. The acceptance interval is shorter.

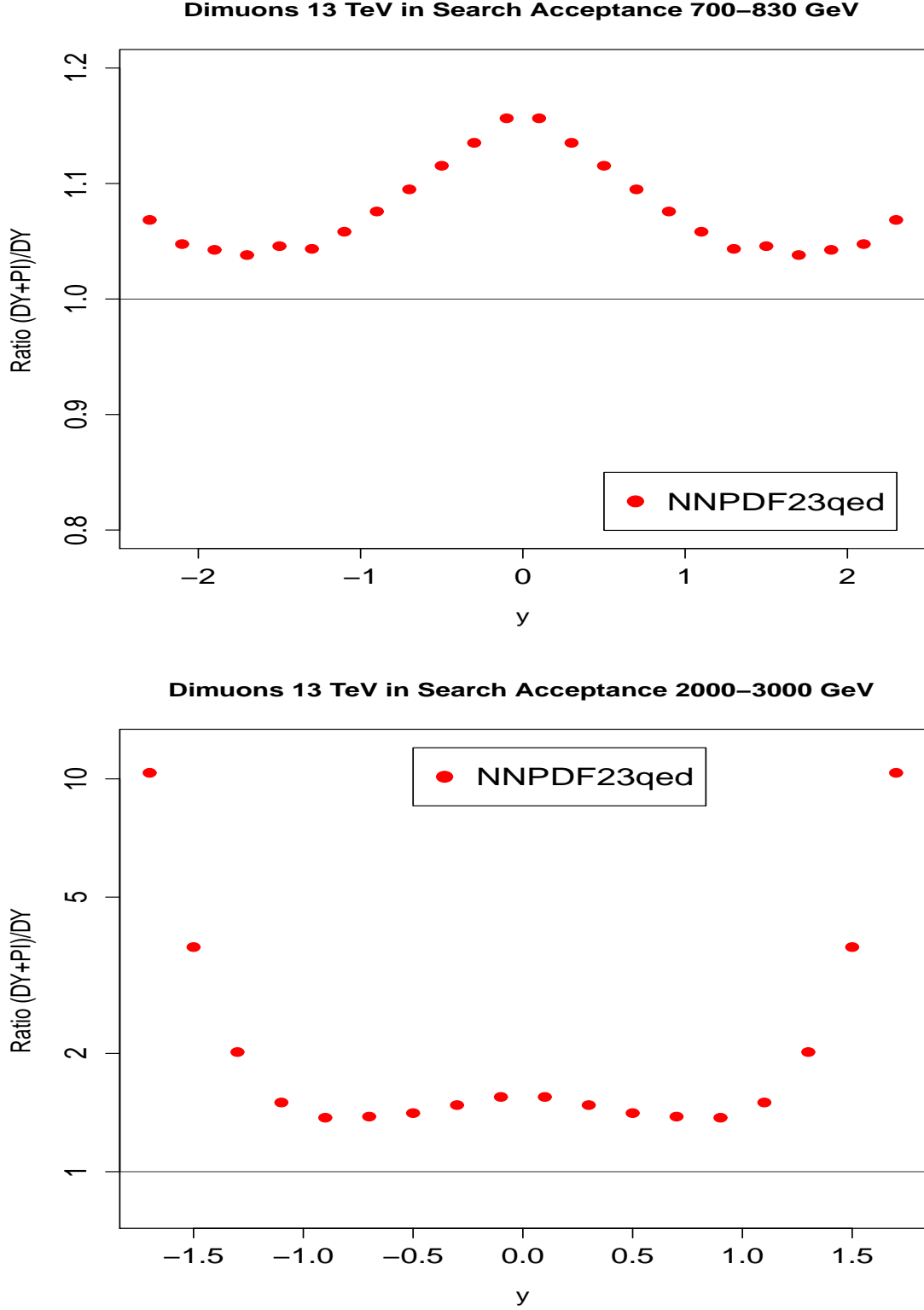


Figure 7: Top: rapidity distribution for $(DY+PI)/DY$ using NNPDF23qed for invariant masses 700–830 GeV. Bottom: rapidity distribution for the same ratio for invariant masses 2–3 TeV. Compare with Figure 6.

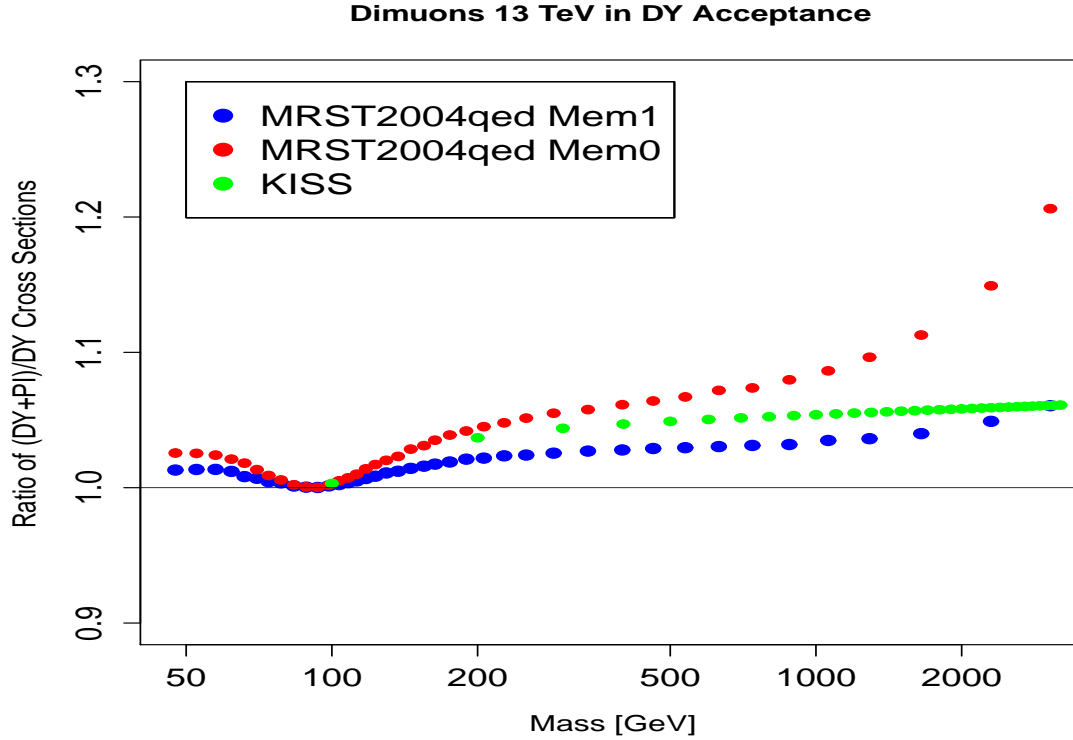


Figure 8: Ratios of cross sections $(DY+PI)/DY$ for MRST2004qed and the KISS estimate in the DY acceptance. A simple approach produces estimates well within the MRST2004qed band.

References

- [1] S. Chatrchyan *et al.* [CMS Collaboration], “Search for Resonances in the Dilepton Mass Distribution in pp Collisions at $\sqrt{s} = 7$ TeV,” JHEP **1105** (2011) 093 doi:10.1007/JHEP05(2011)093 [arXiv:1103.0981 [hep-ex]].
- [2] V. Khachatryan *et al.* [CMS Collaboration], “Search for physics beyond the standard model in dilepton mass spectra in proton-proton collisions at $\sqrt{s} = 8$ TeV,” JHEP **1504** (2015) 025 doi:10.1007/JHEP04(2015)025 [arXiv:1412.6302 [hep-ex]].
- [3] G. Aad *et al.* [ATLAS Collaboration], “Search for high-mass dilepton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” Phys. Rev. D **90** (2014) no.5, 052005 doi:10.1103/PhysRevD.90.052005 [arXiv:1405.4123 [hep-ex]].
- [4] G. Aad *et al.* [ATLAS Collaboration], “Search for contact interactions and large extra dimensions in the dilepton channel using proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” Eur. Phys. J. C **74** (2014) no.12, 3134 doi:10.1140/epjc/s10052-014-3134-6 [arXiv:1407.2410 [hep-ex]].
- [5] “Physics at LEP2,” CERN 96-01, pp.291-348, Geneva, 1996.

- [6] The ATLAS collaboration, “Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector,” ATLAS-CONF-2015-081.
- [7] CMS Collaboration, “Search for new physics in high mass diphoton events in proton-proton collisions at 13TeV ,” CMS-PAS-EXO-15-004.
- [8] C. Csaki, J. Hubisz, S. Lombardo and J. Terning, “Gluon vs. Photon Production of a 750 GeV Diphoton Resonance,” arXiv:1601.00638 [hep-ph].
- [9] A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, “Parton distributions incorporating QED contributions,” Eur. Phys. J. C **39** (2005) 155 doi:10.1140/epjc/s2004-02088-7 [hep-ph/0411040].
- [10] D. Bourilkov, “Study of parton density function uncertainties with LHAPDF and PYTHIA at LHC,” hep-ph/0305126.
- [11] M. R. Whalley, D. Bourilkov and R. C. Group, “The Les Houches accord PDFs (LHAPDF) and LHAGLUE,” hep-ph/0508110.
- [12] D. Bourilkov, R. C. Group and M. R. Whalley, “LHAPDF: PDF use from the Tevatron to the LHC,” hep-ph/0605240.
- [13] S. Chekanov *et al.* [ZEUS Collaboration], “Observation of isolated high $E(T)$ photons in deep inelastic scattering,” Phys. Lett. B **595** (2004) 86 doi:10.1016/j.physletb.2004.05.033 [hep-ex/0402019].
- [14] R. D. Ball *et al.* [NNPDF Collaboration], “Parton distributions with QED corrections,” Nucl. Phys. B **877** (2013) 290 doi:10.1016/j.nuclphysb.2013.10.010 [arXiv:1308.0598 [hep-ph]].
- [15] C. Schmidt, J. Pumplin, D. Stump and C.-P. Yuan, “CT14QED PDFs from Isolated Photon Production in Deep Inelastic Scattering,” arXiv:1509.02905 [hep-ph].
- [16] S. Chekanov *et al.* [ZEUS Collaboration], “Measurement of isolated photon production in deep inelastic ep scattering,” Phys. Lett. B **687** (2010) 16 doi:10.1016/j.physletb.2010.02.045 [arXiv:0909.4223 [hep-ex]].
- [17] S. Chatrchyan *et al.* [CMS Collaboration], “Exclusive photon-photon production of muon pairs in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$,” JHEP **1201** (2012) 052 doi:10.1007/JHEP01(2012)052 [arXiv:1111.5536 [hep-ex]].
- [18] V. Khachatryan *et al.* [CMS Collaboration], “Evidence for exclusive gamma-gamma to $W^+ W^-$ production and constraints on anomalous quartic gauge couplings at $\sqrt{s} = 7$ and 8 TeV ,” arXiv:1604.04464 [hep-ex].
- [19] M. Ababekri, S. Dulat, J. Isaacson, C. Schmidt and C.-P. Yuan, “Implication of CMS data on photon PDFs,” arXiv:1603.04874 [hep-ph].
- [20] Y. Li and F. Petriello, “Combining QCD and electroweak corrections to dilepton production in FEWZ,” Phys. Rev. D **86** (2012) 094034 doi:10.1103/PhysRevD.86.094034 [arXiv:1208.5967 [hep-ph]].